

Influence of O₂ and N₂ on the conductivity of carbon nanotube networks

D. J. Mowbray^{1,*}, C. Morgan², and K. S. Thygesen¹

¹*Department of Physics, Center for Atomic-scale Materials Design (CAMD),
Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark*

²*Department of Physics, Molecular and Materials Physics Group,
Queen Mary University of London, Mile End Road, London E1 4NS, United Kingdom*
(Received 11 February 2009; Published 22 May 2009)

We have performed experiments on single-wall carbon nanotube (SWNT) networks and compared with density-functional theory (DFT) calculations to identify the microscopic origin of the observed sensitivity of the network conductivity to physisorbed O₂ and N₂. Previous DFT calculations of the transmission function for isolated pristine SWNTs have found physisorbed molecules have little influence on their conductivity. However, by calculating the four-terminal transmission function of crossed SWNT junctions, we show that physisorbed O₂ and N₂ do affect the junction's conductance. This may be understood as an increase in tunneling probability due to hopping via molecular orbitals. We find the effect is substantially larger for O₂ than for N₂, and for semiconducting rather than metallic SWNTs junctions, in agreement with experiment.

PACS numbers: 73.63.-b, 68.43.-h, 73.50.Lw

I. INTRODUCTION

Using single-wall carbon nanotubes (SWNTs) as nanosensors, both individually and in SWNT networks, has been one of the most promising potential applications of SWNTs since their discovery.^{1,2} Several experimental studies have demonstrated that the conductance of SWNT systems is rather sensitive to the presence of even single-molecule concentrations of physisorbed gas molecules such as O₂ and N₂.³⁻⁹ Further, by measuring conductivity of individually characterized SWNTs,¹⁰ as well as thick (metal-like) and thin (semiconductor-like) SWNT networks,^{8,9,11} the response of SWNTs to contaminants has been shown to correlate with the intrinsic electronic properties of the material. For example, it has been found that the presence of low-O₂ concentrations, independent of temperature, introduces an increase in conductance of approximately 20% on thin SWNT networks, while an increase in conductance of only about 1% is found for thick SWNT networks.⁸

On the other hand, previous theoretical studies have found that SWNTs are rather inert, so that gases tend only to physisorb to the SWNT surface.¹²⁻¹⁹ For this reason, it was suggested that O₂ should not effect conductance through SWNTs, but only influence conductance at either SWNT-SWNT junctions, at the SWNT-metal contacts, or at SWNT defect sites.^{12,20} Although the conductivity of SWNTs with molecules physisorbed at defect sites has been extensively studied,²¹⁻²³ the conductivity of four-terminal SWNT-SWNT junctions has been previously studied only for small pristine metallic SWNTs.^{24,25} The possible influence of physisorbed molecules on SWNT-SWNT junctions has not been investigated.

In this paper we address the microscopic origin of the increase in conductance of SWNT networks when exposed to O₂ or N₂ gas. To this end, we have performed density-functional theory (DFT) calculations of the intratube transmission within a SWNT and the intertube transmission between two SWNTs in the nonequilibrium Green's function (NEGF) formalism for O₂ and N₂ molecules physisorbed in

(7,7) metallic armchair, (12,0) semimetallic zigzag, and (13,0) semiconducting zigzag SWNT junctions, shown schematically in Fig. 1. Comparing our theoretical results for SWNT junctions with experimental measurements for SWNT networks suggests that the surprising sensitivity to O₂ and N₂ may be partially due to an increased tunneling probability through O₂ and N₂ physisorbed at SWNT junctions.

In Sec. II we describe experimental measurements of the influence of both O₂ and N₂ on the conductivity of SWNT networks and the characterization of these networks using Raman spectroscopy. A description of the DFT and NEGF model used to describe the microscopic origin of this effect is then provided in Sec. III. In Sec. IV we compare our theoretical results for the SWNT junction transmission with the SWNT network experiments, followed by a concluding section.

II. EXPERIMENTAL RESULTS

Below we give a brief discussion of our experiments on SWNT network conductivity. A more detailed description may be found in Refs. 8 and 9. Figure 2 shows experimental measurements of the conductance sensitivity to O₂ and N₂

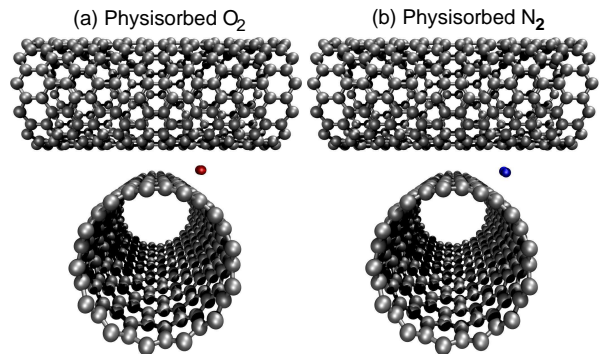


FIG. 1: (Color online) Schematics of a (13,0) SWNT junction with (a) physisorbed O₂ and (b) physisorbed N₂.

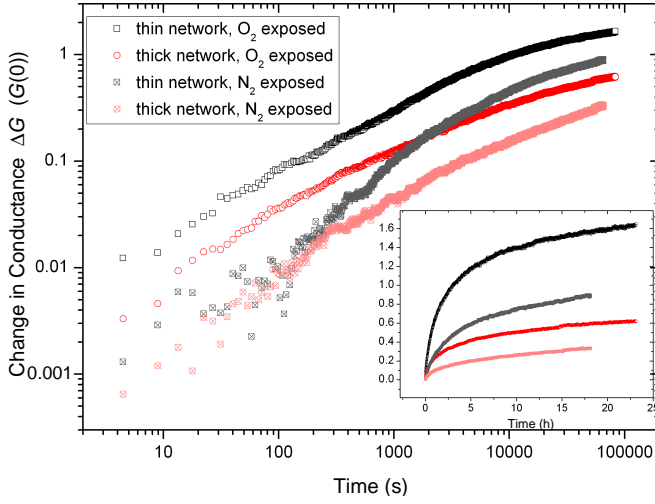


FIG. 2: (Color online) Fractional change in conductance $\Delta G = G/G(0) - 1$ versus time t in seconds and hours (inset) following exposure to O_2 and N_2 for thin (\square , \boxtimes) and thick (\circ , \otimes) SWNT networks respectively, on log-log and linear (inset) scales (Refs. 8 and 9).

exposure for thick and thin SWNT networks. These samples were initially placed under vacuum ($\sim 1 \times 10^{-6}$ mbar) and irradiated by a UV light-emitting diode (LED) ($\lambda \sim 400$ nm) at low intensity (~ 0.03 mW/cm²) for approximately 12 h to desorb surface and interbundle adsorbates (surface dopants) from the SWNTs. Once the SWNT network's conductance stabilized, the samples were exposed to either O_2 (99.5% pure) or N_2 (99.998% pure) at 1 atm. The conductance of the samples was then monitored by periodically sampling ($\Delta t \approx 1$ s) the current while applying a fixed bias of 1 mV to the thick (metal-like) SWNT network ($R \approx 1$ k Ω) and 10 mV to the thin (semiconductor-like) SWNT network ($R \approx 1000$ k Ω), as shown in Fig. 2.

After 5 min of exposure to O_2 , the thin network shows an increase in conductance of about 13% while the thick network's conductance changes by about 7%. For the same exposure to N_2 , both networks show substantially smaller conductance changes of 2%–3%. However, at exposure times of more than 2 h, the thin SWNT network response to N_2 is similar to that of the thick SWNT network to O_2 . This might be caused by a weaker physisorption of N_2 to the SWNT networks than O_2 . The inset of Fig. 2 also shows that at very long exposure times the fractional change in conductance, $\Delta G = G/G(0) - 1$, becomes saturated after 24 h. Further, the response to O_2 depicted in Fig. 2 shows that the conductance change for a thin SWNT network is about two to three times that of the thick SWNT network at all times. This suggests that the conductance change under O_2 exposure is an intrinsic property of the SWNT networks, present even at very low O_2 concentrations. Herein we shall focus on the microscopic origin of the network sensitivity to O_2 and N_2 , with the temporal behavior of the networks discussed elsewhere.^{8,9}

We have performed the Raman spectroscopy to characterize our SWNT network samples, which were produced via

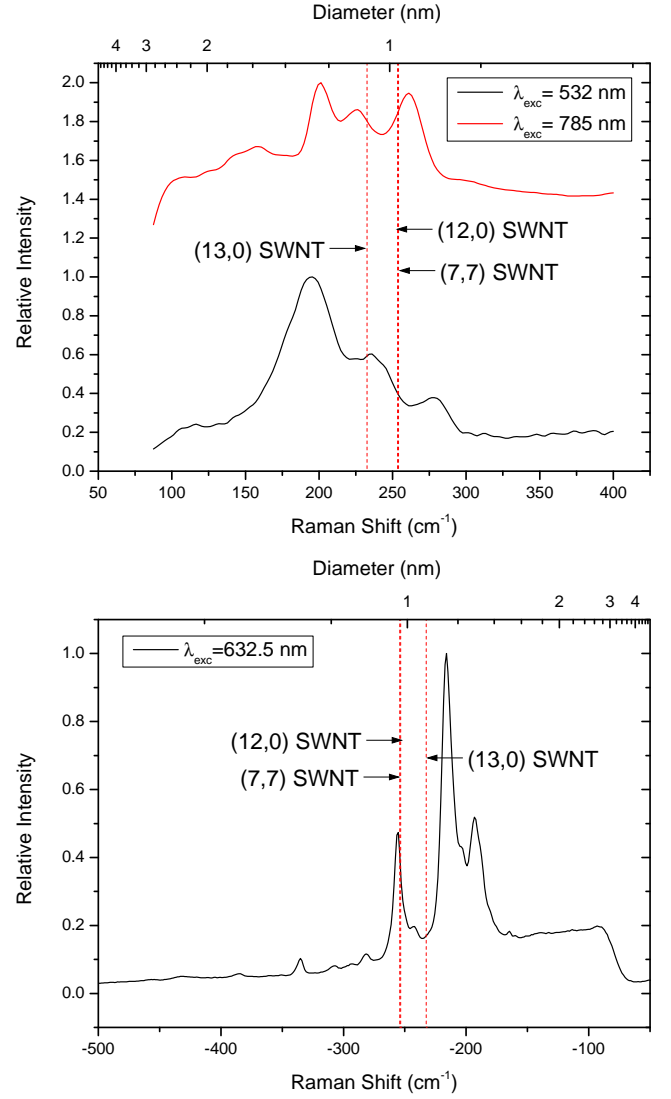


FIG. 3: (Color online) Raman spectra and approximate diameter distribution of HiPco SWNT sample for an excitation wavelength (top) $\lambda_{\text{exc}} \approx 532$ nm (lower black curve), $\lambda_{\text{exc}} \approx 785$ nm (upper red curve), and (bottom) $\lambda_{\text{exc}} \approx 632.5$ nm (—). The DFT calculated diameters of $d \approx 9.76$ Å, 9.79 Å, and 10.66 Å for (7,7), (12,0), and (13,0) SWNTs, respectively, are provided for comparison (dashed lines).

the high-pressure carbon monoxide (HiPco) method. Figure 3 shows the radial breathing mode (RBM) Raman signals of HiPco samples at excitation wavelengths $\lambda_{\text{exc}} \approx 532$ nm, $\lambda_{\text{exc}} \approx 632.5$ nm and $\lambda_{\text{exc}} \approx 785$ nm. The van Hove singularity energy separation was calculated using the tight-binding approximation with the carbon-carbon interaction energy $\gamma_0 \approx 2.9$ eV and carbon-carbon bond length $a_{\text{C-C}} \approx 1.44$ Å. The SWNT diameter d dependence of the RBM frequency ν_{RBM} for isolated SWNTs on SiO_2 has been shown²⁶ to behave as $\nu_{\text{RBM}} \approx 248/d_t$. The DFT calculated diameters for (7,7), (12,0), and (13,0) SWNTs of $d \approx 9.76$, 9.79 , and 10.66 Å, respectively, are found to correlate well with the HiPco Raman shift, as shown in Fig. 3. This should ensure a good de-

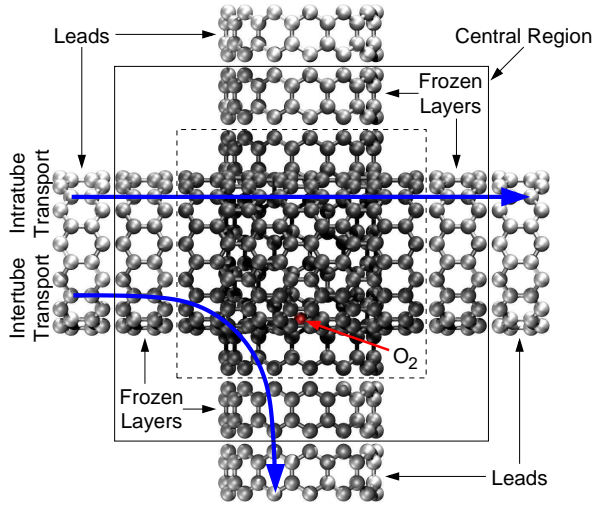


FIG. 4: (Color online) Schematic of (13,0) SWNT junction consisting of four SWNT leads (light gray) coupled to the central scattering region via four SWNT primitive unit cells or layers (gray) “frozen” at their relative positions in the isolated SWNT. The atomic positions of the remaining eight SWNT layers (dark gray) and the physisorbed O₂ molecule have been relaxed. A SWNT separation consistent with experiments of approximately 3.4 Å has been used. The intratube transport through the SWNT and the intertube transport between the SWNTs has been shown schematically.

scription of the SWNT network’s work function, which may be significantly different for smaller tubes.

III. BASIC THEORY

Our DFT calculations have been performed with the SIESTA DFT code^{27,28} using a double-zeta polarized (DZP) basis set for the physisorbed molecules (O and N), and a single-zeta polarized (SZP) basis set for the SWNTs (C), and the Perdew-Burke-Ernzerhof exchange-correlation functional.²⁹ We note here that the DZP and SZP SIESTA basis sets have recently been shown to yield transmission functions in quantitative agreement with plane-wave codes and maximally localized Wannier functions.³⁰ When modeling O₂ we have performed spin-polarized calculations¹² but have performed spin-unpolarized calculations otherwise.

We have modeled the junction system using 6(11) primitive unit cells or layers for each zigzag/armchair SWNT per supercell, with a separation of approximately 3.4 Å, as depicted for a (13,0) SWNT junction in Figs. 1 and 4.³¹ The four SWNT layers at the boundaries of the central region, shown in gray in Fig. 4, were kept fixed at their relaxed positions in the isolated SWNT. At the same time the central 4(9) primitive unit cells from each tube, shown in dark gray in Fig. 4, and the physisorbed molecules were relaxed until a maximum force of less than 0.1 eV/Å was obtained. Since the supercell has dimensions of $\gtrsim 25$ Å for each SWNT junction, a Γ point calculation was sufficient to describe the periodicity of the structure.

Such a large supercell was necessary for the Hamiltonian

TABLE I: Change in intertube conductance ΔG_{inter} at the valence-band maximum ε_{VB} relative to the pristine junction for O₂ and N₂ physisorbed in SWNT junctions of (7,7), (12,0), and (13,0) SWNTs, with the respective SWNT-O₂ and SWNT-N₂ separations d in Angstrom.

SWNT Junction	ΔG_{inter} (%)		d [Å]	
	O ₂	N ₂	SWNT-O ₂	SWNT-N ₂
(7,7) Armchair	30	6	2.3	2.8
(12,0) Zigzag	140	14	2.6	2.8
(13,0) Zigzag	1800	130	2.5	2.8

of each of the four SWNT layers adjacent to the boundaries H_C^{prin} , to be within 0.1 eV of the Hamiltonian for the respective leads H_α , so that $\max |H_C^{\text{prin}} - H_\alpha| < 0.1$ eV. In this way the electronic structure at the edges of the central region was ensured to be converged to that in the leads.

The Landauer-Büttiker conductance for a multi-terminal system can be calculated from the Green’s function of the central region, G_C , according to the formula^{32–34}

$$G = G_0 \text{Tr}[G_C \Gamma_{\text{in}} G_C^\dagger \Gamma_{\text{out}}] \Big|_{\varepsilon=\varepsilon_F}, \quad (1)$$

where the trace runs over all localized basis functions in the central region. To describe the conductance at small bias for semiconducting systems, the Fermi energy ε_F should be taken as the energy of the valence-band maximum ε_{VB} or conduction-band minimum ε_{CB} for p -type and n -type semiconductors, respectively. The central region Green’s function is calculated from

$$G_C(\varepsilon) = \left[zS_C - H_C - \sum_\alpha \Sigma_\alpha(\varepsilon) \right]^{-1}, \quad (2)$$

where $z = \varepsilon + i0^+$, S_C and H_C are the overlap matrix and Kohn-Sham Hamiltonian matrix of the central region in the localized basis, Σ_α is the self-energy of lead α ,

$$\Sigma_\alpha(\varepsilon) = [zS_{C\alpha} - H_{C\alpha}] [zS_\alpha - H_\alpha]^{-1} [zS_{C\alpha}^\dagger - H_{C\alpha}^\dagger], \quad (3)$$

and the coupling elements between the central region and lead α for the overlap and Kohn-Sham Hamiltonian are $S_{C\alpha}$ and $H_{C\alpha}$ respectively.

The coupling strengths of the input and output leads are then given by $\Gamma_{\text{in/out}} = i(\Sigma_{\text{in/out}} - \Sigma_{\text{in/out}}^\dagger)$. For a four-terminal SWNT junction, the intratube and intertube transmission functions are calculated by choosing the appropriate output lead, as depicted in Fig. 4.

IV. THEORETICAL RESULTS & DISCUSSION

For each of the three types of SWNT junctions considered, we find that both O₂ and N₂ are physisorbed with binding energies of ~ 0.2 eV, as depicted in Fig. 1. Further, the SWNT-O₂ and SWNT-N₂ equilibrium separation distance d is in the

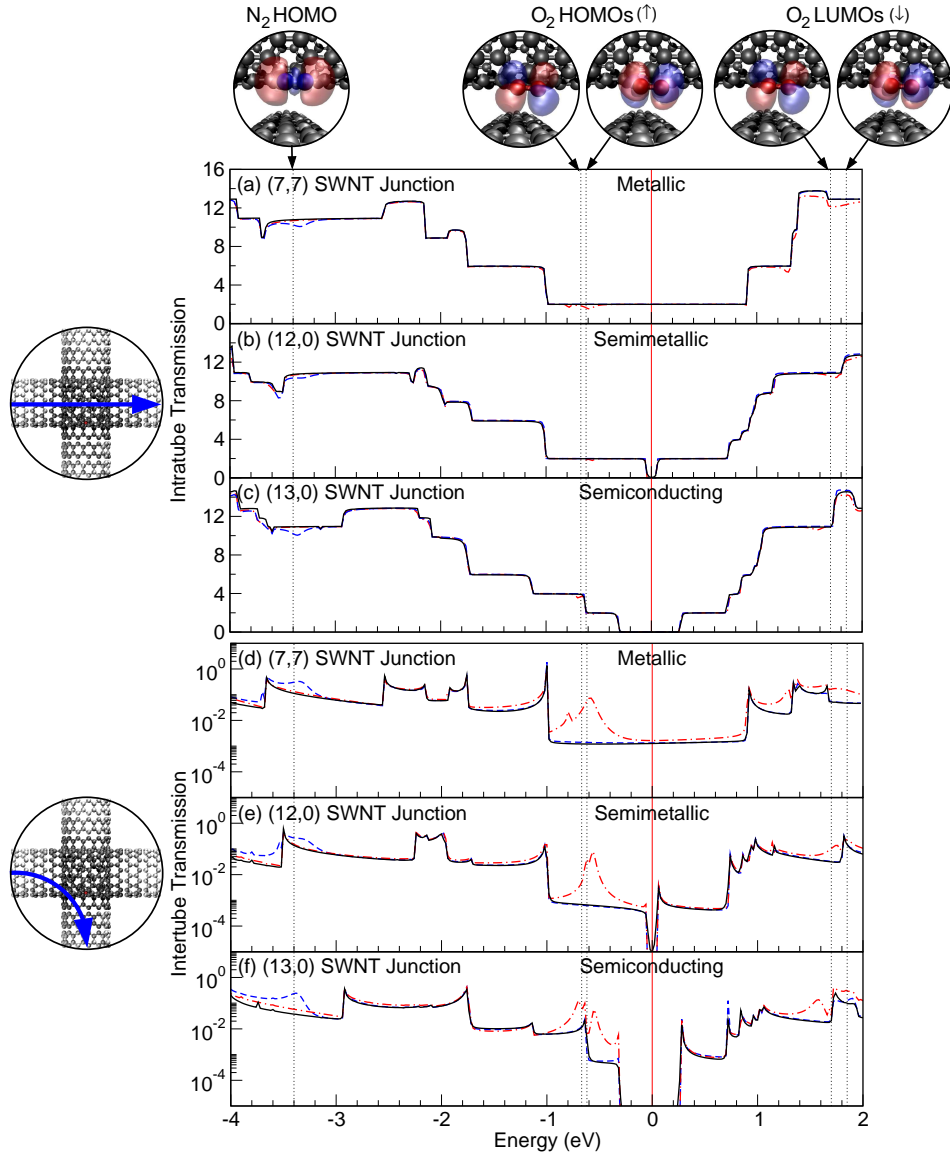


FIG. 5: (Color online) (a)–(c) Intratube transmission and (d)–(f) intertube transmission vs energy in eV relative to the Fermi energy for a pristine (black solid curves) SWNT junction, and with N₂ (blue dashed curves), and O₂ (red dash-dotted curves) physisorbed consisting of [(a) and (d)] metallic (7,7) SWNTs, [(b) and (e)] semimetallic (12,0) SWNTs, and [(c) and (f)] semiconducting (13,0) SWNTs. Schematics and isosurfaces of $\pm 0.02e/\text{\AA}^3$ for molecular orbitals on the physisorbed molecules are shown above the corresponding eigenenergies (dotted lines).

range 2.3–2.8 Å, as given in Table I. These results agree qualitatively with previous theoretical studies for O₂ binding distances and energies on isolated SWNTs.^{12–19}

Figures 5(a)–5(c) show the intratube transmission for three prototypical SWNTs commonly found in experimental HiPco samples,³⁵ as shown in Fig. 3. In Fig. 5(a) we see that for a metallic armchair (7,7) SWNT, transmission occurs through two channels at the Fermi level. We see in Fig. 5(b) that the conductance for the semimetallic zigzag (12,0) SWNT resembles that found in Fig. 5(a) for a metallic SWNT, except for a tiny band gap of $\lesssim 0.05$ eV at the Fermi level. In Fig. 5(c) we find for a semiconducting zigzag (13,0) SWNT a band gap of approximately 0.6 eV between the valence and conduction bands, through which no transmission oc-

curs. This is only slightly smaller than the expected band gap of ~ 0.7 eV, based on a d^{-1} fit to experimental data.³⁶ These results for the intratube transmission of pristine SWNTs also agree qualitatively with previous DFT studies of isolated (5,5), (10,10), (10,5), (11,0), and (12,0) SWNTs.^{25,37,38} We also find in Figs. 5(a)–5(c) that neither O₂ nor N₂ physisorbed at a SWNT junction noticeably influence the intratube transmission.

In Fig. 5 we also show isosurfaces and eigenenergies for the highest occupied and lowest occupied molecular orbitals (HOMO and LUMO) on physisorbed O₂ and N₂. For these weakly coupled molecules, the renormalized molecular levels may easily be identified with the molecular orbitals of the free O₂ and N₂ molecules.³⁹ Since the position of the molecular

levels is rather insensitive to the type of junction, it should also be insensitive to the exact binding geometry. This suggests that additional physisorbed molecules will influence the intertube transmission similarly.

We find the intertube transmission is proportional to the density of states (DOS) for the system with peaks in the transmission at the van Hove singularities. This is consistent with transport between the SWNTs occurring in the tunneling regime, as expected for a SWNT separation of approximately 3.4 Å.

The presence of physisorbed molecules in the SWNT-SWNT gap should then increase the tunneling probability at energies near the eigenenergies of the molecular orbitals. This is evidenced by the distinct peaks in the intertube transmission for each SWNT junction at energies corresponding to the HOMO of N₂ and the spin polarized HOMOs and LUMOs of O₂, as seen in Figs. 5(d)–5(f). Under such conditions, a SWNT junction behaves as a simple tunneling electron microscopy (TEM) tip. By applying appropriate bias voltages, one may potentially probe the molecular orbitals of a physisorbed molecule to determine its chemical composition.

For this reason, the sensitivity of SWNT network conductivity to O₂ is at least partly due to the close proximity of the O₂ HOMOs to the Fermi energies of typical SWNTs (≈ 0.6 eV), as shown in Fig. 5. Further, it has been shown experimentally that defects inherent in physically realizable SWNTs yield *p*-type semiconductors.^{1,40,41} The conductivity measured experimentally at small bias is thus at the energy of the valence band ε_{VB} .

As seen in Fig. 5(f), the O₂ HOMO eigenenergy is only about 0.3 eV below ε_{VB} for a semiconducting (13,0) SWNT junction. As shown in Table I, this yields a substantial increase in the intertube conductance at zero bias for semiconducting junctions in the presence of O₂, while much smaller increases are found for the metallic and semimetallic junctions, in agreement with experiment.⁸ On the other hand, we also find physisorbed N₂ increases the intertube conductance

only slightly, also in qualitative agreement with experiment,⁵ as shown in Fig. 2.

Although it is well-known DFT calculations underestimate band gaps,^{37,42,43} since we are primarily interested in how the presence of O₂ or N₂ qualitatively changes the DOS and conductance, such calculations are still useful.

V. CONCLUSIONS

In conclusion, we have proposed a possible microscopic explanation for the experimentally observed sensitivity of the electrical conductance of carbon nanotube networks to oxygen and nitrogen gases. Our DFT calculations suggests that O₂ and N₂ physisorbed in crossed SWNT junctions can have a large influence on the intertube conductance. In particular, for O₂ the close proximity of the highest occupied molecular orbitals with the Fermi level of the SWNT significantly increases electron tunneling across the gap. The effect is found to be larger for O₂ than for N₂ and for semiconducting rather than metallic SWNTs, in agreement with the experimental observations. Our results suggests that the electrical properties of SWNT networks are to a large extent determined by crossed SWNT junctions.

Acknowledgments

We thank E. I. Kauppinen, and K. W. Jacobson for useful discussions. D.J.M. and K.S.T. acknowledge financial support from NABIIT and the Danish Center for Scientific Computing under Grant No. HDW-1103-06. The Center for Atomic-scale Materials Design (CAMD) is sponsored by the Lundbeck Foundation. C. M. acknowledges financial support from the National Physical Laboratory (NPL) and the Engineering and Physical Sciences Research Council (EPSRC-GB).

* Electronic address: dmowbray@fysik.dtu.dk

¹ M. S. Dresselhaus, G. Dresselhaus, and P. Avouris, eds., *Carbon Nanotubes: Synthesis, Structure, Properties, and Applications* (Springer, Berlin, 2001).

² D. R. Kauffman and A. Star, “Carbon nanotube gas and vapor sensors”, *Angew. Chem.* **47**(35), 6550 (Jul. 2008), doi:[10.1002/anie.200704488](https://doi.org/10.1002/anie.200704488).

³ K. Bradley, S.-H. Jhi, P. G. Collins, J. Hone, M. L. Cohen, S. G. Louie, and A. Zettl, “Is the intrinsic thermoelectric power of carbon nanotubes positive?”, *Phys. Rev. Lett.* **85**(20), 4361 (Nov. 2000), doi:[10.1103/PhysRevLett.85.4361](https://doi.org/10.1103/PhysRevLett.85.4361).

⁴ P. G. Collins, K. Bradley, M. Ishigami, and A. Zettl, “Extreme oxygen sensitivity of electronic properties of carbon nanotubes”, *Science* **287**(5459), 1801 (Mar. 2000), doi:[10.1126/science.287.5459.1801](https://doi.org/10.1126/science.287.5459.1801).

⁵ G. U. Sumanasekera, C. K. W. Adu, S. Fang, and P. C. Eklund, “Effects of gas adsorption and collisions on electrical transport in single-walled carbon nanotubes”, *Phys. Rev. Lett.* **85**(5), 1096 (Jul. 2000), doi:[10.1103/PhysRevLett.85.1096](https://doi.org/10.1103/PhysRevLett.85.1096).

⁶ A. Felten, J. Ghijsen, J.-J. Pireaux, R. L. Johnson, C. M. Whelan, D. Liang, G. V. Tendeloo, and C. Bittencourt, “Effect of oxygen rf-plasma on electronic properties of CNTs”, *J. Phys. D* **40**(23), 7379 (Dec. 2007), doi:[10.1088/0022-3727/40/23/019](https://doi.org/10.1088/0022-3727/40/23/019).

⁷ M. Kaempgen, M. Lebert, M. Haluska, N. Nicoloso, and S. Roth, “Sonochemical optimization of the conductivity of single-wall carbon nanotube networks”, *Adv. Mater.* **20**(3), 616 (Jan. 2008), doi:[10.1002/adma.200702873](https://doi.org/10.1002/adma.200702873).

⁸ C. Morgan, Z. Alemipour, and M. Baxendale, “Variable range hopping in oxygen-exposed single-wall carbon nanotube networks”, *Phys. Stat. Solidi A* **205**(6), 1394 (2008), doi:[10.1002/pssa.200778113](https://doi.org/10.1002/pssa.200778113).

⁹ C. Morgan and M. Baxendale, “Diffusion of O₂ and N₂ through thin and thick SWNT networks” (May 2009), [arXiv:0905.1821v1](https://arxiv.org/abs/0905.1821v1).

¹⁰ J. Kong, N. R. Franklin, C. Zhou, M. G. Chapline, S. Peng, K. Cho, and H. Dai, “Nanotube molecular wires as chemical sensors”, *Science* **287**(5453), 622 (Jan. 2000), doi:[10.1126/science.287.5453.622](https://doi.org/10.1126/science.287.5453.622).

- ¹¹ V. Skákalová, A. B. Kaiser, Y.-S. Woo, and S. Roth, “Electronic transport in carbon nanotubes: From individual nanotubes to thin and thick networks”, *Phys. Rev. B* **74**(8), 085403 (Aug. 2006), doi:[10.1103/PhysRevB.74.085403](https://doi.org/10.1103/PhysRevB.74.085403).
- ¹² P. Giannozzi, R. Car, and G. Scoles, “Oxygen adsorption on graphite and nanotubes”, *J. Chem. Phys.* **118**(3), 1003 (Jan. 2003), doi:[10.1063/1.1536636](https://doi.org/10.1063/1.1536636).
- ¹³ A. Tchernatinsky, S. Desai, G. U. Sumanasekera, C. S. Jayanthi, S. Y. Wu, B. Nagabhirava, and B. Alphenaar, “Adsorption of oxygen molecules on individual single-wall carbon nanotubes”, *J. Appl. Phys.* **99**, 034306 (Feb. 2006), doi:[10.1063/1.2163008](https://doi.org/10.1063/1.2163008).
- ¹⁴ V. A. Margulis and E. E. Muryumin, “Atomic oxygen chemisorption on the sidewall of zigzag single-walled carbon nanotubes”, *Phys. Rev. B* **75**(3), 035429 (Jan. 2007), doi:[10.1103/PhysRevB.75.035429](https://doi.org/10.1103/PhysRevB.75.035429).
- ¹⁵ S. Peng and K. Cho, “Chemical control of nanotube electronics”, *Nanotechnology* **11**(2), 57 (Jun. 2000), doi:[10.1088/0957-4484/11/2/303](https://doi.org/10.1088/0957-4484/11/2/303).
- ¹⁶ D. C. Sorescu, K. D. Jordan, and P. Avouris, “Theoretical study of oxygen adsorption on graphite and the (8,0) single-walled carbon nanotube”, *J. Phys. Chem. B* **105**(45), 11227 (Oct. 2001), doi:[10.1021/jp0122979](https://doi.org/10.1021/jp0122979).
- ¹⁷ D. J. Mann and W. L. Hase, “Direct dynamics simulations of the oxidation of a single wall carbon nanotube”, *Phys. Chem. Chem. Phys.* **3**(19), 4376 (Aug. 2001), doi:[10.1039/b103762p](https://doi.org/10.1039/b103762p).
- ¹⁸ S.-H. Jhi, S. G. Louie, and M. L. Cohen, “Electronic properties of oxidized carbon nanotubes”, *Phys. Rev. Lett.* **85**(8), 1710 (2000), doi:[10.1103/PhysRevLett.85.1710](https://doi.org/10.1103/PhysRevLett.85.1710).
- ¹⁹ S.-P. Chan, G. Chen, X. G. Gong, and Z.-F. Liu, “Oxidation of carbon nanotubes by singlet O₂”, *Phys. Rev. Lett.* **90**(8), 086403 (Feb. 2003), doi:[10.1103/PhysRevLett.90.086403](https://doi.org/10.1103/PhysRevLett.90.086403).
- ²⁰ A. R. Rocha, M. Rossi, A. Fazzio, and A. J. R. da Silva, “Designing real nanotube-based gas sensors”, *Phys. Rev. Lett.* **100**(17), 176803 (May 2008), doi:[10.1103/PhysRevLett.100.176803](https://doi.org/10.1103/PhysRevLett.100.176803).
- ²¹ S. Peng and K. Cho, “Ab initio study of doped carbon nanotubes sensors”, *Nano Lett.* **3**(4), 513 (Mar. 2003), doi:[10.1021/nl034064u](https://doi.org/10.1021/nl034064u).
- ²² P. C. P. Watts, N. Mureau, Z. Tang, Y. Miyajima, J. D. Carey, and S. R. P. Silva, “The importance of oxygen-containing defects on carbon nanotubes for the detection of polar and non-polar vapours through hydrogen bond formation”, *Nanotechnology* **18**(17), 175701 (May 2007), doi:[10.1088/0957-4484/18/17/175701](https://doi.org/10.1088/0957-4484/18/17/175701).
- ²³ P. C. P. Watts, W.-K. Hsu, H. W. Kronto, and D. R. M. Walton, “Are bulk defective carbon nanotubes less electrically conducting?”, *Nano Lett.* **3**(4), 549 (Mar. 2003), doi:[10.1021/nl034028v](https://doi.org/10.1021/nl034028v).
- ²⁴ M. S. Fuhrer, J. Nygård, L. Shih, M. Forero, Y.-G. Yoon, M. S. C. Mazzoni, H. J. Choi, J. Ihm, S. G. Louie, A. Zettl, and P. L. McEuen, “Crossed nanotube junctions”, *Science* **288**(5465), 494 (Apr. 2000), doi:[10.1126/science.288.5465.494](https://doi.org/10.1126/science.288.5465.494).
- ²⁵ Y.-G. Yoon, M. S. C. Mazzoni, H. J. Choi, J. Ihm, and S. G. Louie, “Structural deformation and intertube conductance of crossed carbon nanotube junctions”, *Phys. Rev. Lett.* **86**(4), 688 (Jan. 2001), doi:[10.1103/PhysRevLett.86.688](https://doi.org/10.1103/PhysRevLett.86.688).
- ²⁶ A. Jorio, R. Saito, J. H. Hafner, C. M. Lieber, M. Hunter, T. McClure, G. Dresselhaus, and M. S. Dresselhaus, “Structural (n, m) determination of isolated single-wall carbon nanotubes by resonant raman scattering”, *Phys. Rev. Lett.* **86**(6), 1118 (Feb. 2001), doi:[10.1103/PhysRevLett.86.1118](https://doi.org/10.1103/PhysRevLett.86.1118).
- ²⁷ S. R. Bahn and K. W. Jacobsen, “An object-oriented scripting interface to a legacy electronic structure code”, *Comput. Sci. Eng.* **4**(3), 56 (May 2002), doi:[10.1109/5992.998641](https://doi.org/10.1109/5992.998641).
- ²⁸ J. M. Soler, E. Artacho, J. D. Gale, A. Garcia, J. Junquera, P. Ordejón, and D. Sánchez-Portal, “The SIESTA method for *ab initio* order-*n* materials simulation”, *J. Phys.: Condens. Matter* **14**(11), 2745 (Mar. 2002), doi:[10.1088/0953-8984/14/11/302](https://doi.org/10.1088/0953-8984/14/11/302).
- ²⁹ J. P. Perdew, K. Burke, and M. Ernzerhof, “Generalized gradient approximation made simple”, *Phys. Rev. Lett.* **77**(18), 3865 (Oct. 1996), doi:[10.1103/PhysRevLett.77.3865](https://doi.org/10.1103/PhysRevLett.77.3865).
- ³⁰ M. Strange, I. S. Kristensen, K. S. Thygesen, and K. W. Jacobsen, “Benchmark density functional theory calculations for nanoscale conductance”, *J. Chem. Phys.* **128**(11), 114714 (Mar. 2008), doi:[10.1063/1.2839275](https://doi.org/10.1063/1.2839275).
- ³¹ J. Kleis, P. Hyldgaard, and E. Schröder, “Van der Waals interaction of parallel polymers and nanotubes”, *Comput. Mater. Sci.* **33**(1–3), 192 (Jan. 2005), doi:[10.1016/j.commatsci.2004.12.036](https://doi.org/10.1016/j.commatsci.2004.12.036).
- ³² Y. Meir and N. S. Wingreen, “Landauer formula for the current through an interacting electron region”, *Phys. Rev. Lett.* **68**(16), 2512 (Apr. 1992), doi:[10.1103/PhysRevLett.68.2512](https://doi.org/10.1103/PhysRevLett.68.2512).
- ³³ K. S. Thygesen, “Electron transport through an interacting region: The case of a nonorthogonal basis set”, *Phys. Rev. B* **73**(3), 035309 (Jan. 2006), doi:[10.1103/PhysRevB.73.035309](https://doi.org/10.1103/PhysRevB.73.035309).
- ³⁴ M. Buttiker, “Four-terminal phase-coherent conductance”, *Phys. Rev. Lett.* **57**(14), 1761 (Oct. 1986), doi:[10.1103/PhysRevLett.57.1761](https://doi.org/10.1103/PhysRevLett.57.1761).
- ³⁵ Z. Luo, L. D. Pfefferle, G. I. Haller, and F. Papadimitrakopoulos, “(n,m) abundance evaluation of single-walled carbon nanotubes by fluorescence and absorption spectroscopy”, *J. Am. Chem. Soc.* **128**(48), 15511 (Nov. 2006), doi:[10.1021/ja0657096](https://doi.org/10.1021/ja0657096).
- ³⁶ T. W. Odom, J.-L. Huang, P. Kim, and C. M. Lieber, “Structure and electronic properties of carbon nanotubes”, *J. Phys. Chem. B* **104**(13), 2794 (Feb. 2000), doi:[10.1021/jp993592k](https://doi.org/10.1021/jp993592k).
- ³⁷ S. Reich, C. Thomsen, and P. Ordejón, “Electronic band structure of isolated and bundled carbon nanotubes”, *Phys. Rev. B* **65**(15), 155411 (Apr. 2002), doi:[10.1103/PhysRevB.65.155411](https://doi.org/10.1103/PhysRevB.65.155411).
- ³⁸ J.-C. Charlier, X. Blase, and S. Roche, “Electronic and transport properties of nanotubes”, *Rev. Mod. Phys.* **79**(2), 677 (May 2007), doi:[10.1103/RevModPhys.79.677](https://doi.org/10.1103/RevModPhys.79.677).
- ³⁹ K. S. Thygesen and K. W. Jacobsen, “Molecular transport calculations with Wannier functions”, *Chem. Phys.* **319**(1–3), 111 (Dec. 2005), doi:[10.1016/j.chemphys.2005.05.032](https://doi.org/10.1016/j.chemphys.2005.05.032).
- ⁴⁰ S. J. Tans, A. R. M. Vershueren, and C. Dekker, “Room-temperature transistor based on a single carbon nanotube”, *Nature* **393**, 49 (May 1998), doi:[10.1038/29954](https://doi.org/10.1038/29954).
- ⁴¹ V. Derycke, R. Martel, J. Appenzeller, and P. Avouris, “Carbon nanotube inter- and intramolecular logic gates”, *Nano Lett.* **1**(9), 453 (Sep. 2001), doi:[10.1021/nl015606f](https://doi.org/10.1021/nl015606f).
- ⁴² J. Paier, M. Marsman, K. Hummer, G. Kresse, I. C. Gerber, and J. G. Ángyán, “Screened hybrid density functionals applied to solids”, *J. Chem. Phys.* **124**(15), 154709 (Apr. 2006), doi:[10.1063/1.2187006](https://doi.org/10.1063/1.2187006).
- ⁴³ J. Heyd, J. E. Peralta, G. E. Scuseria, and R. L. Martin, “Energy band gaps and lattice parameters evaluated with the Heyd-Scuseria-Ernzerhof screened hybrid functional”, *J. Chem. Phys.* **123**(17), 174101 (Oct. 2005), doi:[10.1063/1.2085170](https://doi.org/10.1063/1.2085170).